

Monitoring of the thermal neutron flux in the LSM underground laboratory

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Abstract. This paper describes precise measurements of the thermal neutron flux in the LSM underground laboratory in proximity of the EDELWEISS-II dark matter search experiment together with short measurements at various other locations. Monitoring of the flux of thermal neutrons is accomplished using a mobile detection system with low background proportional counter filled with ³He. On average 75 neutrons per day are detected with a background level below 1 count per day (cpd). This provides a unique possibility of a day by day study of variations of the neutron field in a deep underground site. The measured average 4π neutron flux per cm² in the proximity of EDELWEISS-II is $\Phi_{MB} = 3.57 \pm 0.05^{stat} \pm 0.27^{syst} \times 10^{-6}$ neutrons/sec. We report the first experimental observation that the point-to-point thermal neutron flux at LSM varies by more than a factor two.

PACS numbers: 28.20.-v, 29.40.Cs

Submitted to: *J. Phys. G: Nucl. Phys.*

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1. Introduction

The Laboratoire Souterrain de Modane (LSM) [1] is an underground laboratory located in the Fréjus tunnel connecting France and Italy. It has an average rock overburden corresponding to ~ 4850 mwe (meter water equivalent) [2]. This reduces the muon flux by more than 6 orders of magnitude and the neutron flux by 4 orders of magnitude compared to sea level. A principal source of remaining neutrons is natural radioactivity in rock and all other materials located in the laboratory, via spontaneous fission (SF) and (α, n) reactions. Many experiments are located at LSM, the two largest being the EDELWEISS-II [3] direct Dark Matter search and the NEMO-3 [4] experiment searching for neutrinoless double beta decay ($0\nu\beta\beta$). An unbiased interpretation of results from these experiments requires a detailed understanding of all background sources. In the near future, it is planned to enlarge LSM to host the next generation of experiments searching for Dark Matter and $0\nu\beta\beta$. These will require further background reductions and a precise knowledge of the remainder. Thermal neutrons are not a background of concern for present-day experiments, but may become so for future ones where neutron activation of construction materials or the detectors themselves may be an issue. For a correct interpretation of results of dark matter experiments not only the background rate but also its temporal variations are of critical importance. The EDELWEISS-II collaboration performs a wide variety of measurements of neutrons in the proximity of the experimental setup together with Monte Carlo studies (MC) [5]. Experimental studies include: a) the continuous monitoring of fast neutrons since the start of data taking with EDELWEISS-II in 2006; b) the measurement of fast neutrons produced by cosmic muons in the vicinity of the EDELWEISS-II muon veto system; c) the present measurement of thermal neutrons; and d) a feasibility test of cryogenic detectors made of light targets to study the fast neutron background [6].

In this letter we present the study devoted to the measurement and continuous monitoring of the thermal neutron flux at LSM, especially in the proximity of the EDELWEISS-II setup.

2. Thermal neutron detector

The detection of thermal neutrons is provided by a proportional counter tube filled with ^3He gas via the capture reaction $n + ^3\text{He} \rightarrow \text{T} + \text{p}$ ($Q = 0.764$ MeV). The cross section for thermal neutrons on ^3He is $\sigma = 5333 \pm 7$ barn [7]. The CHM-57 counter [9] used in the setup has a working length of 860 mm with an internal diameter of 31 mm. The counter is filled with 400 kPa of ^3He and 500 kPa of ^{40}Ar as working gas. The region of interest for thermal neutron detection are ionization signals with energies around Q . In proportional counters, the main background in this energy range arises from α -decays of U and Th progenies in the walls of the detector. To reduce this background, the CHM-57 counter is covered inside by a 50-60 μm thick layer of Teflon followed by a 1 μm layer of electrolytic copper.

The charge from gas-amplified ionization appearing on the signal wire of the counter is read out by an attached Cremat CR-110 single channel charge sensitive preamplifier module. It generates a tail voltage pulse for the shaping amplifier. The spectroscopy amplifier generates a shaped positive pulse for a 12 bit analog to digital converter (ADC) with an integrated discriminator. The digitized pulses are then transferred to a PC by serial connection. An ORTEC 448 pulse generator

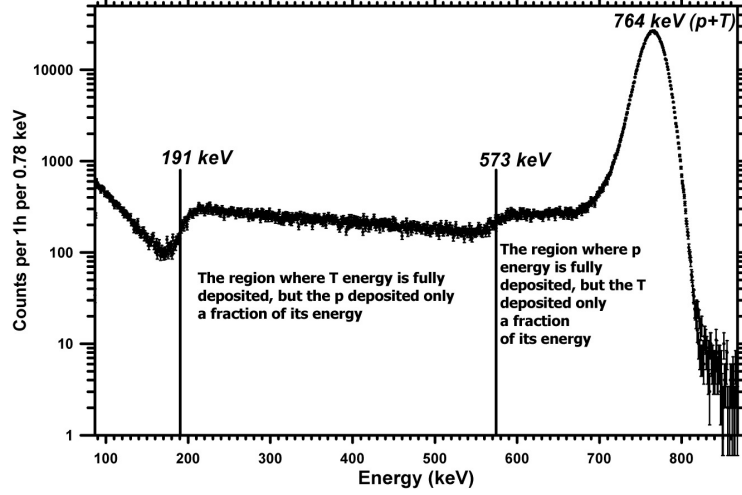


Figure 1. CHM-57 calibration spectrum with exposure to a strong PuBe source (neutrons from which were moderated by ~ 2.5 cm of polyethylene). The vertical lines indicate the kinematic energy of the T (191 keV) and p (573 keV) from the neutron capture on ^3He .

has been used to monitor the electronic chain. Linearity of the energy scale and the proportionality mode of the counter has been verified in the JINR laboratory in Dubna using an intense neutron source. A typical calibration spectrum is shown in Fig. 1. Neutron capture on ^3He near the counter wall leads to the escape of one of the two decay products, either triton (T) or proton. This leads to flanks in the pulse height spectrum as can be seen in Fig. 1 which can be used to control the linearity of the energy scale. This was used for estimation of an uncertainty on the number of counts at energy interval from 660 to 830 keV arising from the energy scale calibration with the single peak. This uncertainty was found to be below of 0.5%. The interval from 660 to 830 keV is the region-of-interest (ROI) used for experimental data analysis (see section 4).

After installation in LSM, the position and the stability of the neutron peak in the pulse height spectrum has been cross-checked with a weak (20 n/sec) AmBe neutron source.

3. Detector sensitivity

The detection sensitivity of the naked ^3He counter CHM-57 for thermal neutrons has been determined using the GEANT4 toolkit [10] with the implementation of the GEANT4 Physics List for low-energy neutron applications QGSP_BIC_HP. For an isotropic (4π) neutron flux at 1 neutron/cm²/sec the sensitivity was found to be respectively 243 counts/sec and 227 counts/sec for 2 cases: first one for Maxwell-Boltzmann distribution $f_{MB}(E) = \frac{E}{(kT_m)^2} \exp(-\frac{E}{kT_m})$; second one for the Maxwell-Boltzmann distribution multiplied by the square root of the energy $f_{MB}(E)\sqrt{E}$, that could take into account effect of thermalization, where $T_m = 293$ K and $E < 0.3$ eV. Hereinafter for determination of flux of thermal neutrons we will use the first value as a traditional description of such neutrons. The second value is needed for the purposes of

illustration of systematic associated with difference of an "ideal" thermal neutron flux and the "real" one. The above sensitivities are determined for a pulse height interval corresponding to the 660–830 keV ROI introduced in previous section (GEANT4 accounts for Proton and Triton energy losses in the counter). The estimation of detector's sensitivity with GEANT4 has been verified in calibration measurements with a source of 944.7 g of depleted ^{238}U where the 4 CHM-57 counters were placed inside a polyethylene moderator. The source had been positioned directly on the moderator's surface. The experimental value of expected neutron flux from 1 kg of natural uranium of 14.9 ± 0.2 Hz was taken from [11]. For our source it corresponds to an expected neutron emission rate at 14.2 ± 0.2 Hz. The calibration measurements were performed at Dubna laboratory at sea level, thus we gave special attention to the study of fluctuations of the natural neutron background. As can be seen in Table 1 no significant fluctuations were observed on the day of measurement. But since we did observe a fluctuation of measurements performed on other days, we derived the value for the background as an average between measurements presented in the table, which is equal to 0.56 Hz. Two background measurements before and after to one with the source have respectively $+0.04$ and -0.01 Hz differences from the average value. To take into account possible unstability of ambient neutron background, uncertainty of the average value was estimated to be 0.04 Hz (as maximal one from two above values). The resulting experimental counting rate from the source is 0.99 ± 0.06 Hz. GEANT4 predicted count rate of 1.035 ± 0.014 Hz (quoted error is from expected source activity only) is in excellent agreement with the measured rate.

Table 1. Background and calibration runs with ^{238}U source performed at Dubna laboratory to check MC prediction of efficiency of CHM-57 counter.

Run start time	Run time	Run type	Counting rate at ROI
11h12	1200 sec	background	0.54 ± 0.02 Hz
11h55	1000 sec	background	0.56 ± 0.02 Hz
12h15	1000 sec	background	0.57 ± 0.02 Hz
13h11	1000 sec	background	0.60 ± 0.02 Hz
13h30	1000 sec	^{238}U +background	1.55 ± 0.04 Hz
14h22	1000 sec	background	0.55 ± 0.02 Hz
16h12	1000 sec	background	0.58 ± 0.02 Hz
16h32	1000 sec	background	0.54 ± 0.02 Hz

4. Experimental setup and results

The thermal neutron monitoring system has been installed at LSM in November 2008. The detector was positioned directly on one of the wall of the laboratory, a few meters away from the EDELWEISS-II setup. This location is shown on Figs. 2 and 3. The close proximity to the wall provides a solid angle of 2π for thermal neutrons emerging directly from the wall. The thermal neutrons coming from the other 2π are most likely affected by materials inside the laboratory, and especially by the massive polyethylene anti-neutron shield of the EDELWEISS-II setup. Such a bias from a pure measurement of the thermal neutron flux due to the natural radioactivity of the rock is unavoidable in a fully-operating laboratory like the LSM. However, the main concern for the EDELWEISS-II experiment is the actual flux in the laboratory in its present state, rather than an ideal "unaffected flux".

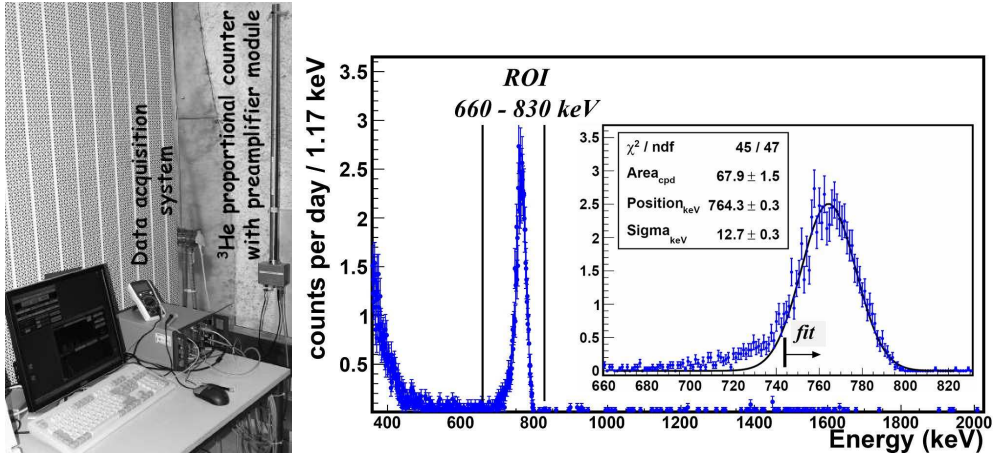


Figure 2. Thermal neutron detection system at LSM (left) and experimental energy spectrum received for 37 days of measurements (right). Place of measurement is point 1, see Fig. 3.

The experimental spectrum recorded from November 4, 2008 to December 10, 2008 (accumulated live time is 35.6 days) is shown in Fig. 2. Another run of data taking was performed from May 27, 2009 to July 27, 2009 (accumulated live time is 52.7 days). The average rate in the ROI from 660 to 830 keV for all time of measurement is 75.3 ± 0.9 cpd. The FWHM resolution of the detector at 764 keV is 4%.

The α -background in the ROI defined above has been estimated to be 0.39 ± 0.04 cpd from the extrapolation of this background from the energy region from 0.9 to 1.3 MeV. This extrapolated value has been confirmed in direct measurements when the detector has been placed inside of additional massive polyethylene shields at LSM. In this study 71 counts were detected in the ROI in 177.8 days of measurements, with no sign of a neutron peak. This corresponds to an alpha background rate in the ROI of 0.40 ± 0.05 cpd, in agreement with the extrapolated value. Taking into account the detector sensitivity and the α background, the observed count rate corresponds to a flux of $\Phi_{MB} = 3.57 \pm 0.05^{\text{stat}} \pm 0.27^{\text{syst}} \times 10^{-6}$ neutrons/cm²/sec for this particular location at LSM under the assumption that the neutron spectrum below 0.3 eV is Maxwell-Boltzmann distribution and that thermal neutron flux is fully isotropic. The systematic error contributions are listed in Table 3. Very often it is more useful to define neutron flux as number of neutrons entering into detector through unit of its surface area (for example, neutron flux on the surface of EDELWEISS). For this purpose our number for all directional 4π flux has to be divided by 2.

We performed additional measurements at various other locations at LSM, further away from the EDELWEISS-II setup. The results are summarized in Table 2. The point 4 corresponds approximately to the place where a thermal neutron flux measurement was performed in 1992, resulting in a flux of $\Phi = 1.6 \pm 0.1 \times 10^{-6}$ neutrons/cm²/sec [8]. This value and the present measurement of $\Phi_{MB} = 2.0 \pm 0.2^{\text{stat}} \pm 0.15^{\text{syst}} \times 10^{-6}$ neutrons/cm²/sec are in reasonable agreement, as the former pre-dates the installation of the present NEMO and EDELWEISS setups.

Table 2 clearly shows that the thermal neutron flux at LSM may vary by up to

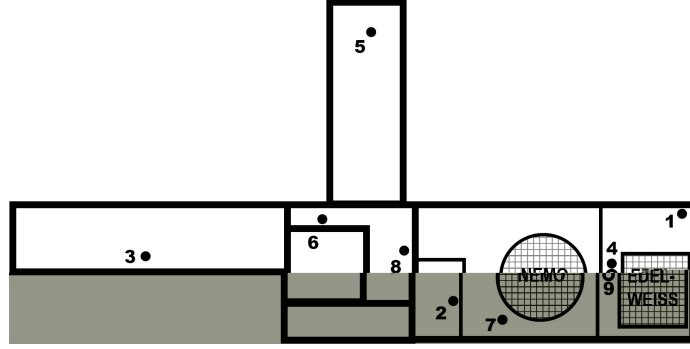


Figure 3. Locations at LSM where measurements of thermal neutron flux have been performed: 1 – main place of measurements; 2 – NEMO preparation clean room; 3 – LSM tambour; 4 – between EDELWEISS and NEMO, approximately same as the point 9 (1992 measurement); 5 – Ge detectors' hall; 6 – LSM control room; 7 – main hall, close to NEMO3 setup; 8 – platform at the main hall. The point 9 is the place of the 1992 measurement [8]. Places 1, 3, and 8 located on the level 0 of the LSM, all other points at the level -2.75 m.

Table 2. Thermal neutron fluxes (10^{-6} /cm²/sec) at different locations at LSM. See Fig. 3 for details. Errors are statistical only, systematic uncertainties are listed in Table 3.

Point	Run time Days	Results		
		Counting rate at ROI, cpd	Flux ¹	Flux ²
1 ³	35.6	76.8±1.5	3.64±0.07	3.90±0.07
1 ⁴	52.7	74.3±1.2	3.52±0.06	3.77±0.06
2	1.13	96.9±9.3	4.6±0.4	4.9±0.5
3	0.89	130.7±12.1	6.2±0.6	6.6±0.6
4	2.75	43.3±4.0	2.0±0.2	2.2±0.2
5	1.00	94.7±9.7	4.5±0.5	4.8±0.5
6	1.17	81.8±8.4	3.9±0.4	4.1±0.4
7	0.91	60.4±8.1	2.9±0.4	3.1±0.4
8	0.83	72.2±9.3	3.4±0.4	3.7±0.5

¹ – Maxwell-Boltzmann distribution

² – Maxwell-Boltzmann multiplied by \sqrt{E}

³ – measurements performed from November 4, 2008 to December 10, 2008

⁴ – measurements performed from June 1, 2009 to July 28, 2009

Table 3. Estimated systematic uncertainties (%).

Active volume	4.6	Detector's sensitivity (MC)	6.2
Background	<0.5	ROI determination	<0.5
Live time	<0.5		
Total systematic error			7.7%

a factor three from one location to an other. In addition to the large neutron shields, additional point-to-point flux variations may be due to other materials present at LSM, and in particular their water content, as well as to inhomogeneities in material and their U/Th contamination. The high efficiency of the neutron detector and the resulting large count rate, as well as the low background rate, make a detailed study

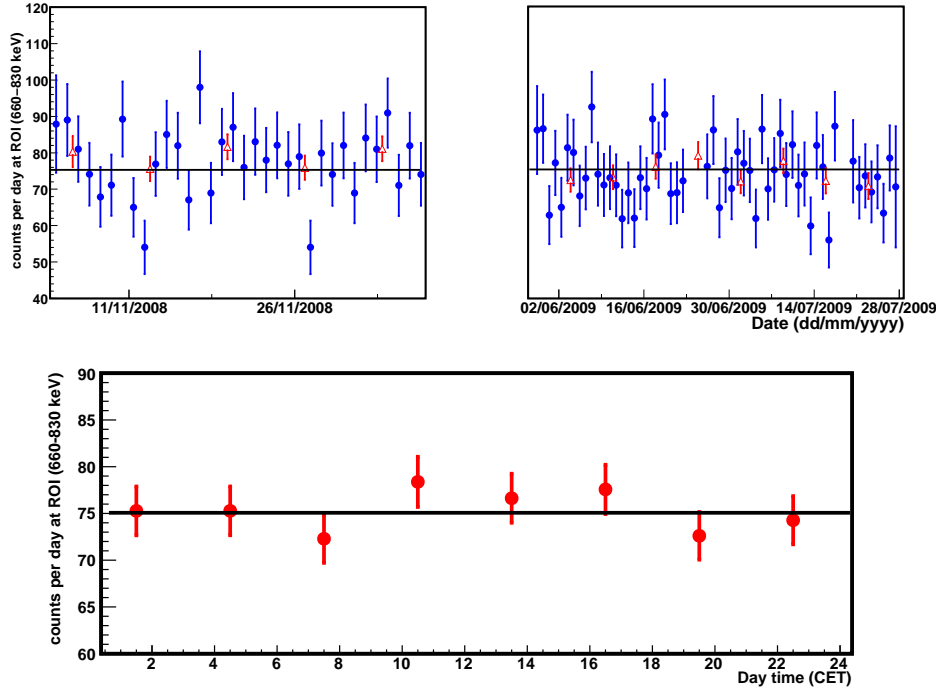


Figure 4. Changes of neutron flux at LSM with time. On the upper plot, points correspond to day by day sampling intervals, triangles correspond to week by week sampling (with weeks starting on Sunday). On the bottom plot, points correspond to particular day time with 3 h step. Lines on all plots are average counts' rate for all time of measurement.

of the variation in time of the thermal neutron flux possible, as shown in Fig. 4 and Table 4. All observed fluctuations are in agreement with statistical expectation.

Table 4. Statistical analysis of time variations of measured neutron flux.

Sampling method	χ^2/ndf^*	χ^2/ndf^+	90% CL	σ at single sample
day / 3h intervals	4.9/7=0.7	$0.5 < \chi^2 < 1.7$		~3.5%
day by day	96/91=1.05	$0.8 < \chi^2 < 1.2$		~11%
week by week	15.6/15=1.04	$0.6 < \chi^2 < 1.5$		~4%

* - fit of experimental data with the assumption that neutron flux is constant with time

+ - both tail's areas of χ^2 distribution (below and above of the interval) are 10%

5. Conclusion

As part of the program of background controls for the EDELWEISS-II experiment environment, the thermal neutron flux is monitored using a ^3He filled bare proportional counter. With a daily count rate of 75 and a background of a fraction of count,

this detector makes possible a continuous day by day monitoring of the thermal neutron flux. No departure from a constant flux with time was measured on scales of 3h/day/week, at a given location. However, variations of the thermal flux as large a factor three were measured between different locations in the laboratory. The flux close to the laboratory wall at the proximity of the EDELWEISS-II setup is $\Phi_{MB} = 3.57 \pm 0.05^{stat} \pm 0.27^{syst} \times 10^{-6}$ neutrons/cm²/sec under the assumption that the neutron spectrum follows a Maxwell-Boltzmann distribution and that thermal neutron flux is isotropic.

6. Acknowledgements

The EDELWEISS collaboration is grateful to the LSM laboratory that provided service for work underground and highly valuable technical assistance. We would like to give special recognition to B. Branlard for his valuable contribution to works performed at LSM. We are obliged to Dr. Yu. Shitov for his experienced help with Geant4 simulations. This work has been partly supported by Russian Foundation for Basic Research (grant No. 07-02-00355-a) and ILIAS (TARI project P2008-01-LSM).

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